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Case Evaluation of a Surface Seismic Reflection Technique for Delineating Coalbed Discontinuities

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UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	mm	millimeter
ft/s	foot per second	ms	millisecond
Hz	hertz	pct	percent
in	inch	s	second
lb	pound	yr	year
mi^2	square mile		

CASE EVALUATION OF A SURFACE SEISMIC REFLECTION TECHNIQUE FOR DELINEATING COALBED DISCONTINUITIES

By Gregory M. Molinda[1] and David K. Ingram[1]

ABSTRACT

Coalbed discontinuities historically have been hazardous to mining as well as obstructions to efficient production. An effective means of mapping these features is needed in order to plan safe and efficient mine development. This Bureau of Mines report discusses the use of surface seismic techniques for this purpose.

At a southwestern Pennsylvania mine, a system of coalbed discontinuities (paleochannels) was accurately mapped by the Bureau of Mines using borehole log methods and underground observation. This site was chosen to test the value of a high-resolution surface seismic reflection technique for coalbed mapping.

A statistical study performed at this mine indicated that the probability of accurately delineating this paleochannel system with conventional borehole methods was remote.

A total of 1.47 miles of high-resolution seismic survey, comprised of four seismic profiles, was conducted in known and suspected coalbed discontinuity areas. Several test holes were drilled on the seismic lines in order to evaluate the interpretations. It was found, based on these and other existing boreholes, that it is possible to predict these discontinuities. Paleochannel washouts were correctly predicted in several instances but in other instances were either incorrectly predicted or not predicted in areas of known discontinuities.

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INTRODUCTION

Discontinuities are defined as structures that interrupt the lateral continuity of a coalbed. The hazards of encountering discontinuities within minable coalbeds have been well documented (1).[2] Equally important is the adverse economic effect to the coal industry in terms of lost production, sterilized reserves, inefficient development, and the cost of extraordinary roof support. The intention of this report is to evaluate the effectiveness of high-resolution seismic reflection in delineating coalbed discontinuities large enough to affect mining safety and production.

Coalbed discontinuities have historically been linked to hazards such as unstable roof conditions, high gas emissions, and methane ignition. In particular, the emission of methane into the mine atmosphere can be influenced by coalbed discontinuities. Discontinuities such as paleochannels can be reservoirs for gas or water and, when intercepted by mining, can act to compartmentalize a coalbed reservoir. High-pressure methane may build up in these isolated cells. Also, coalbed discontinuities can hinder methane drainage efforts by deflecting boreholes or obstructing free migration of gas to the wellbore. Figure 1 illustrates the degree to which a coalbed reservoir can be interrupted by a discontinuity.

These structures can cause mining problems that can only be solved when coalbeds can be accurately mapped in advance of mining. Although general trends can be identified, the accurate local mapping of discontinuities by exploration drilling alone is nearly impossible.

The cost of rotary drilling prohibits increasing the drilling density in order to provide the necessary coverage. Other problems include access and right-of-way. What is needed is a remote sensing technique that can provide accurate delineation of subsurface features at reasonable cost. One such technique, high-resolution surface seismic reflection, has shown promise toward this end. Recent adaptations of oilfield technology

[2]Underlined numbers in parentheses refer to items in the list of references preceding the appendix.

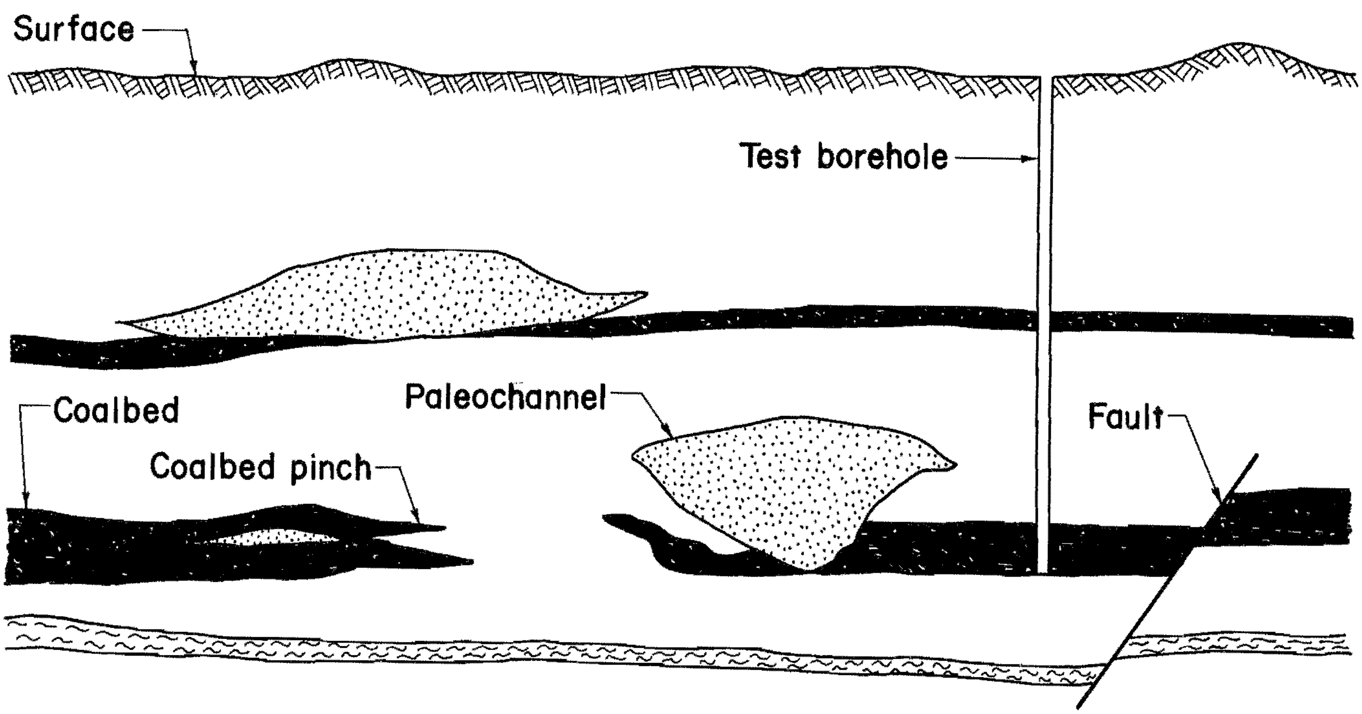

FIGURE 1.—Coalbed discontinuities.

to shallow coalbed exploration have located paleochannels on the order of several hundred feet wide (2). Seismic reflection has also been used to delineate abandoned mine workings and burn cavities in underground gasification projects, as well as complicated structural features.

The Bureau of Mines field-tested a high-resolution seismic reflection technique at a site particularly well suited for this evaluation. The coalbed discontinuities affecting the Pittsburgh Coalbed at this site were well documented by both drilling data and underground observation.

UNCERTAINTY OF DELINEATING COALBED DISCONTINUITIES WITH CONVENTIONAL METHODS

Coalbeds are commonly widespread, laterally continuous, blanket deposits, but can be interrupted by a number of structures, including faults, clay veins, channel washouts, splits, rolls, and pinchouts, depending on the local depositional environment and the subsequent regional tectonic history. A coalbed can have any or all of these structures.

The conventional way to conduct an exploration program on a coal property is by drilling a pattern of boreholes. The developer will drill on a preselected grid with boreholes spaced on 1/2- to 1-mile centers. However, geologic features (paleochannel systems, faults, coalbed pinchouts, local structures) that could disrupt or limit the development of a resource often occur on a much smaller scale. These features and their trends could easily be missed by drilling on a grid of 1-mile centers.

Of particular interest to the present study are the depositional features known as paleochannels. Ancient distributary systems created vast wetlands for peat deposition as they emptied into inland seas. The sinuous distributary channels meandered across the depositional plain in response to changes in stream load, sea level, and local warping. These stream channels eventually become filled with silt and sand; it is at the contact of this channel fill with surrounding roof strata that hazardous roof conditions can occur. In figure 2, a hypothetical distributary channel system is overprinted with a standard exploration drilling grid; it is clear that such a grid could easily miss the bulk of the channel system.

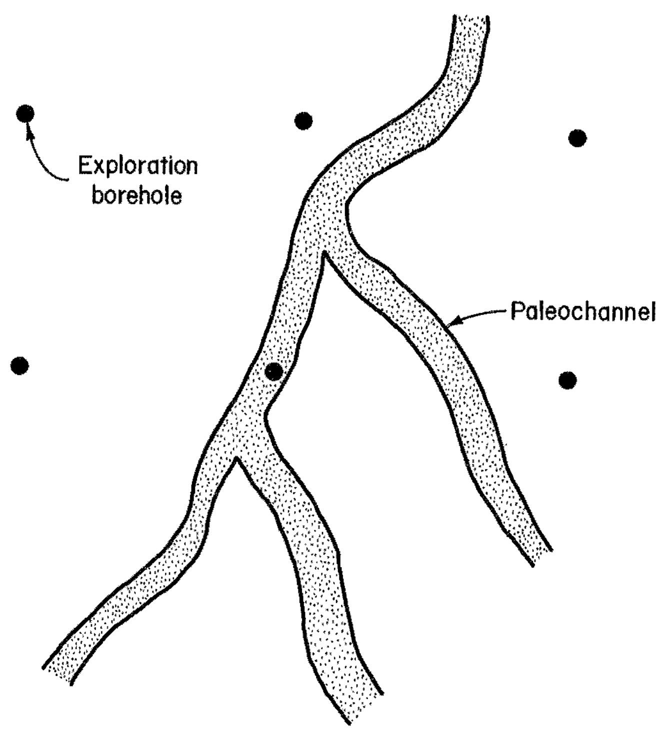

FIGURE 2.—Hypothetical distributary paleochannel system with overprinted exploration borehole grid.

CHARACTER OF PALEOCHANNELS WITHIN THE STUDY AREA

The Pittsburgh Coalbed is of minable thickness over large parts of Pennsylvania, Ohio, and West Virginia (fig. 3) and is considered one of the most valuable fuel resources in the world. It is included in the Pittsburgh Formation of the Monongahela Group in the Upper Pennsylvanian System. Though remarkably persistent over a vast area, this coalbed is frequently intersected by local paleochannel systems.

The Gateway coal mine is located in Green County in southwestern Pennsylvania. It has been worked in the Pittsburgh Coalbed for over 50 yr, with a present annual production of 1.8 million tons. Extensive underground mapping in the western portion of the mine shows a paleochannel system that has influenced mining in the area (fig. 4). The general northwest-southwest trend of the system correlates with a regional trend previously identified (3).

The individual discontinuities are elongate sinuous pods which may erode all or part of the coalbed. Paleochannels can be filled with either siltstone or sandstone depending on the energy regime of the environment. The paleochannels can also occur in the roof and can be totally undetected up until undermining. At this point, strata between the channel fill and the mine opening may loosen and fall, or at least necessitate supplemental support measures.

The paleochannels range in width from 20 ft to over 430 ft and in length from 75 ft to over 2,625 ft. The largest one identified was of sufficient size to cause the operators to change their mining plan. The West Mains section was repositioned 800 ft to the south, and a barrier pillar was left to the east of the 8 Face section because a "want"[3] was also suspected (fig. 4).

[3]A want is a localized disappearance of a coal seam due to faulting, washout, or pinchout.

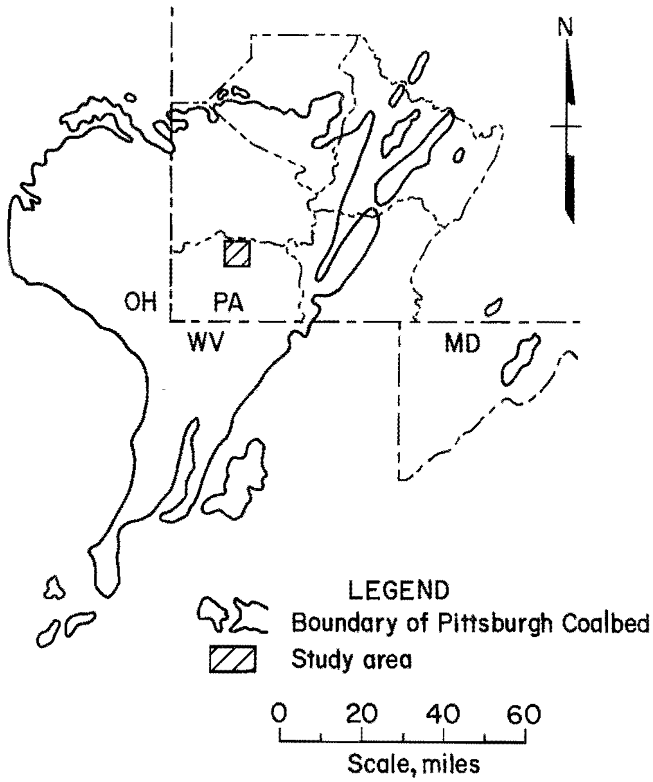

FIGURE 3.—Location of study area and boundary of Pittsburgh Coalbed.

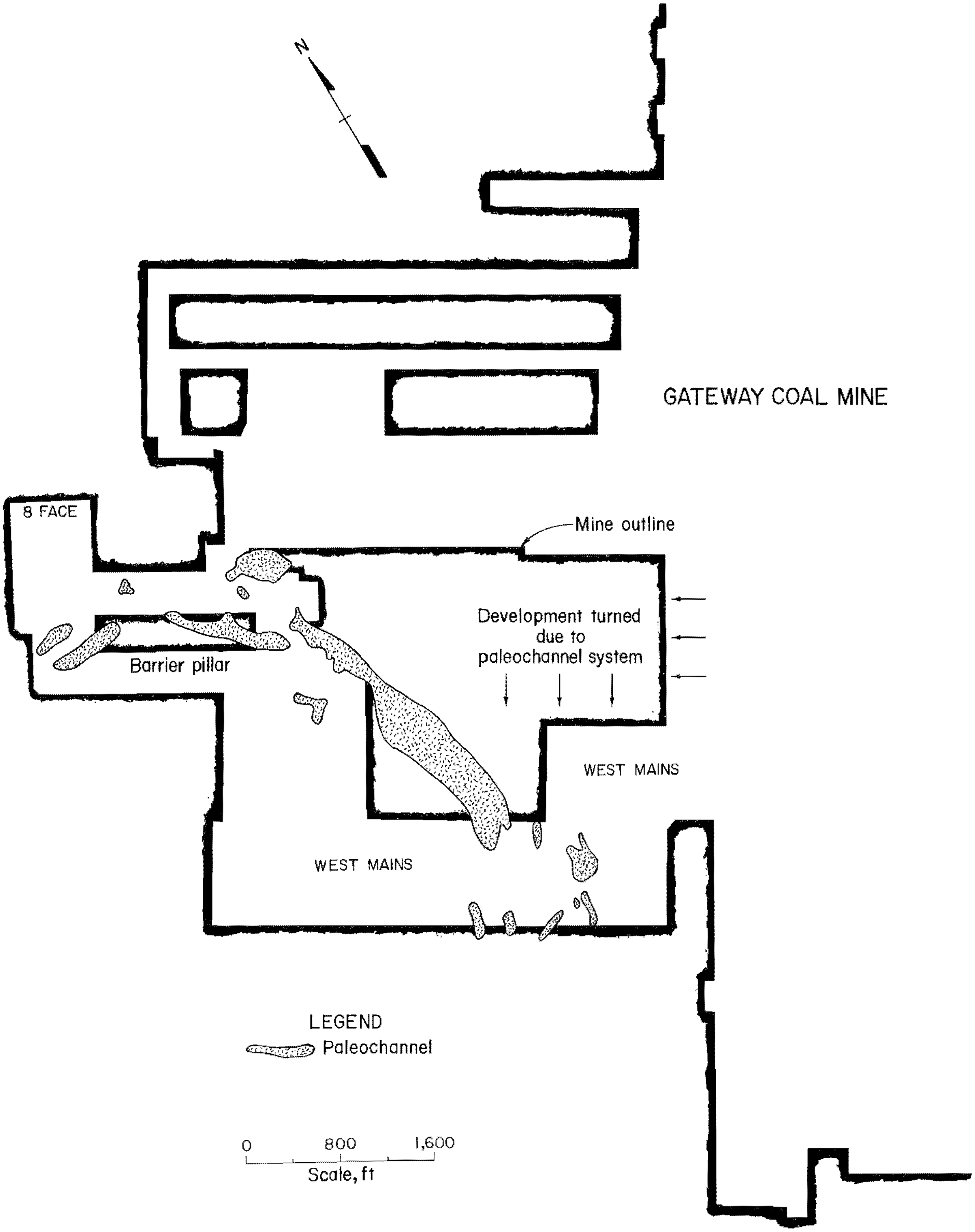

FIGURE 4.—Nature of paleochannel system affecting mining in study area.

HIGH-RESOLUTION SEISMIC REFLECTION

In an effort to evaluate the effectiveness of high-resolution seismic reflection data for determining coalbed continuity, a total of 7,750 ft (1.47 miles) of seismic line subsurface coverage was recorded in three different locations over four separate lines (fig. 5). Lines 1 and 2 were located in a known want area because of good well control and in-mine survey information. The two lines converge to the east over a mined-out area, and line 2 also extends over the mine on its western extension. Lines 3 and 4 were located in virgin coal, based on corehole information that indicated a possible want area. An attempt was made to run lines as close to existing coreholes as possible in order to tie seismic data to well control. A detailed description of the field geometry and acquisition program is included in the appendix of this report; generally the data were recorded with single geophones and shot points spaced on 20-ft centers. This arrangement is designed to give subsurface data points every 10 ft. The energy source used was a Mapco 21-mm Seisgun[5] that provided a useful range of high-frequency energy. The gun fires a 3-oz lead slug into the ground and is capable of successive firings for data stacking. The data are recorded on magnetic tape and sent for final processing. Computer processing of the magnetic tapes includes filtering noise, elevation and position statics, waveform normalization, and editing. Finally, human interpretations are made on the processed record.

A useful preliminary step to interpreting seismic data is the construction of a synthetic seismogram. This plot represents the integration of subsurface rock velocities and enables correlation of production reflections with actual lithologic horizons. Gateway No. 1 test hole was drilled in order to provide downhole information (velocities and rock densities) for this calibration exercise. Sonic log, linear density log, and check-shot velocity survey were run downhole for this purpose.

Complete seismic time-distance records were generated for all four of the production lines. From these records subsurface cross sections were made as well as isopach and structure contour maps.

For a mapping technique to be useful to mine planning, it is necessary to achieve the following resolution:

1. Coalbed thickness: ≥5.0 ft
2. Faulting: offset ≥5.0 ft
3. Discontinuity: paleochannels ≥100 ft wide
4. Coalbed rolls: elevation accuracy to ±5.0 ft

The results of the seismic survey are evaluated based on these criteria on a line-by-line basis.

LINES 1 AND 2 RESULTS

Figure 6 is the fully processed, interpreted seismic record for line 1. Three different horizons were targeted for tracking: horizon A (an interpreted unconformable surface), horizon B-C (the Waynesburg Coal interval), and horizon D-E (the Pittsburgh Coal interval).

The main target objective, the Pittsburgh horizon, is indicated by the lineup of the variable-area peaks of individual reflections (approximately 0.12 s, horizon D-E). This particular reflection band choice as the Pittsburgh Coalbed is based on the log of the Gateway No. 1 well and the synthetic seismogram constructed from downhole velocity data. The Pittsburgh horizon is interpreted as being interrupted at shot points 57-65 (paleochannel), shot point 47 (fault), shot points 26-32 (paleochannel), shot points 12-17 (paleochannel), and shot point 8 (fault) (fig. 6). For the three paleochannels listed above, the interpretation is based on downbowing or termination of the reflector interval. These channels range from 80 to 160 ft wide.

[5]Reference to specific products does not imply endorsement by the Bureau of Mines.

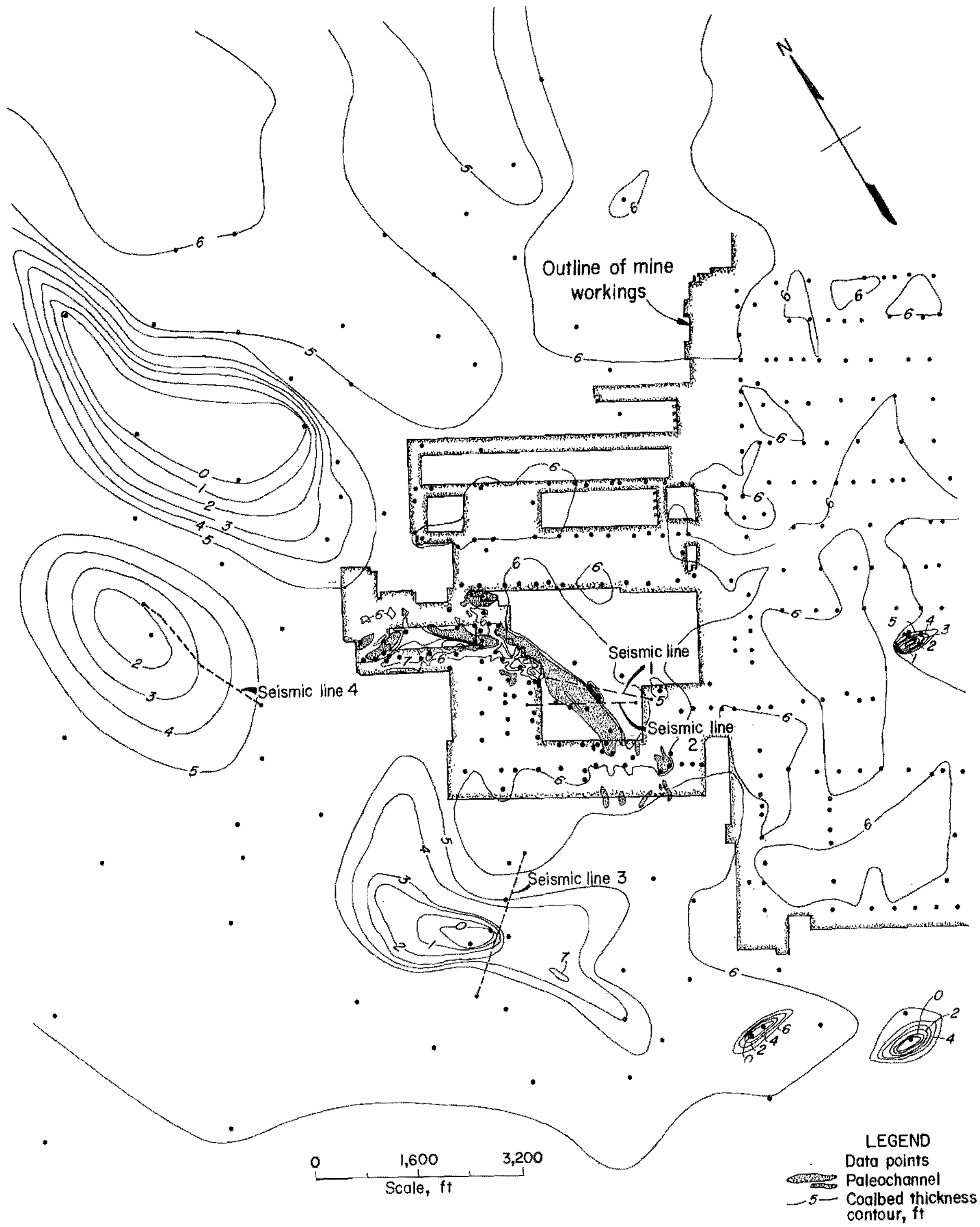

FIGURE 5.—Isopach map of Pittsburgh Coalbed at present extent of mining.

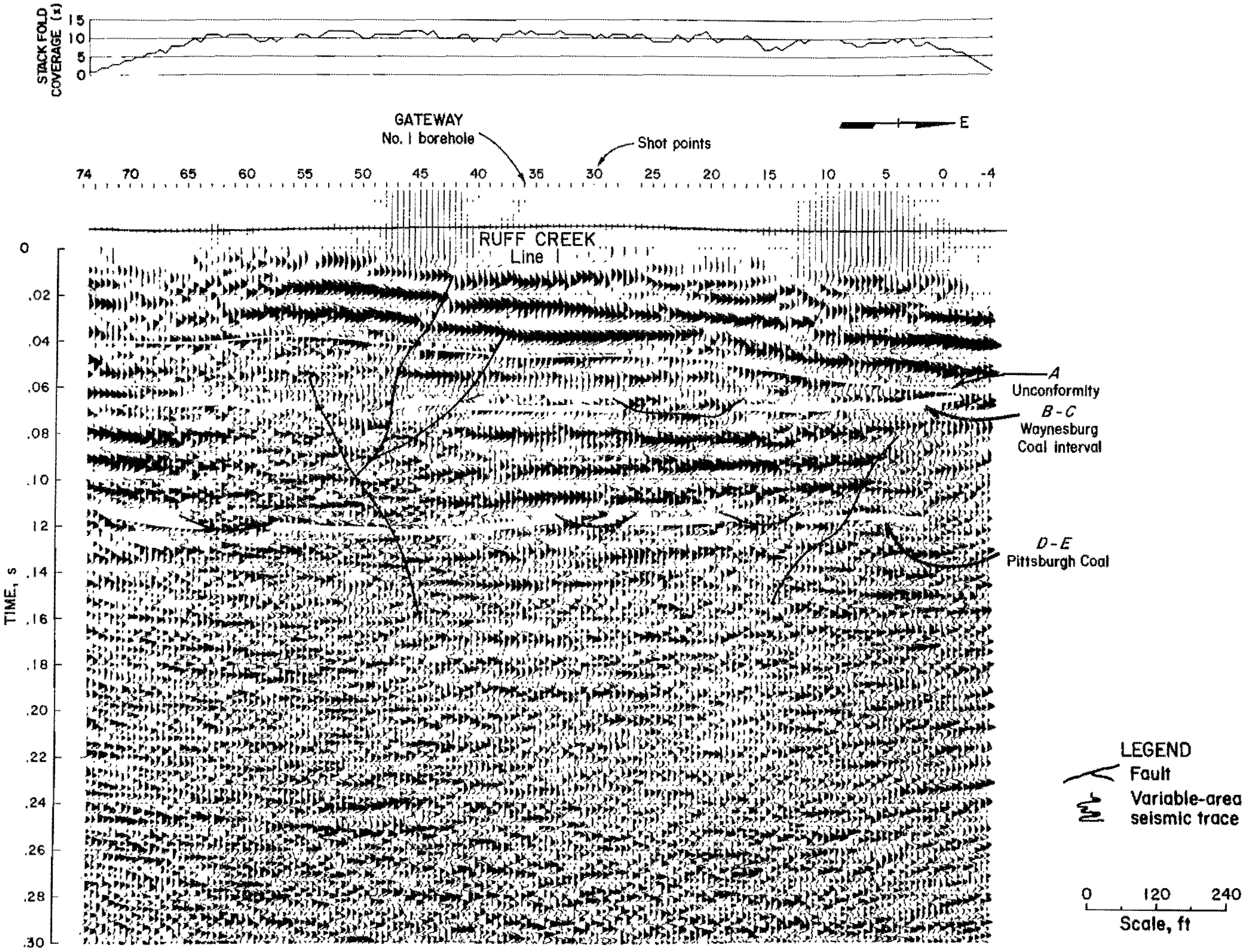

FIGURE 6.—Processed interpreted seismic record for line 1.

The seismically determined channels are in the correct size range when compared with known channels observed underground. Because of the inability to resolve top and bottom horizons seismically, it is impossible to estimate the extent to which the coalbed is affected.

Figure 7 is a structure contour map drawn on top of the Pittsburgh Coalbed at lines 1 and 2. It was constructed using the seismic reflection data and shows the interpreted paleochannel discontinuities interrupting the Pittsburgh Coalbed. Additional features are interpreted fault planes and located exploration holes. It is felt that the interpreted orientation of the channels is reasonable based on three occurrences along line 1 and two occurrences on line 2.

A test hole (Gateway No. 2), showing the Pittsburgh Coalbed was indeed washed out, was drilled at shot point 61 on line 1 to the Pittsburgh horizon and below. The coalbed was replaced by a sandy siltstone. This composition is common for paleochannel fill, based on underground

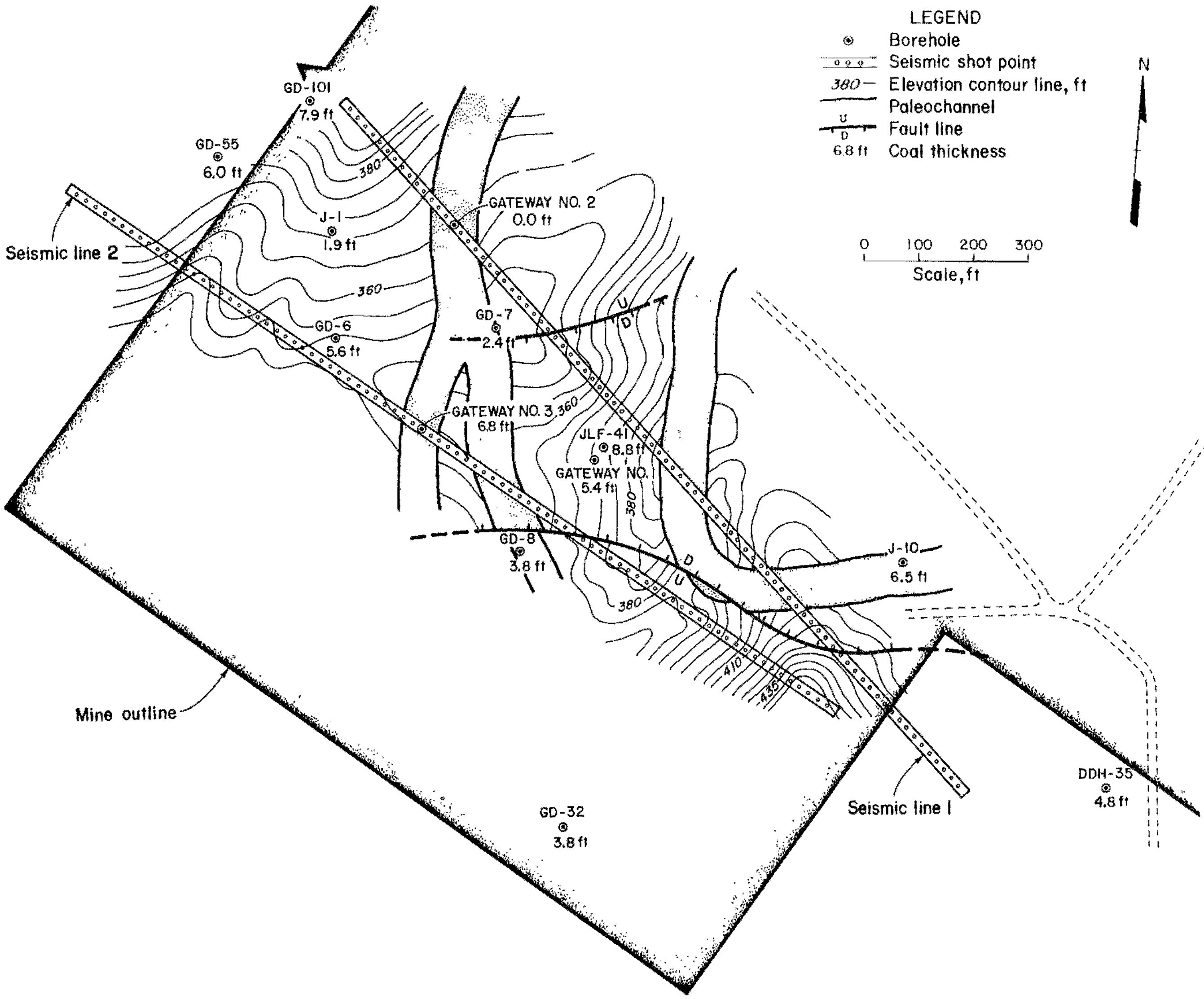

FIGURE 7.—Structure contour map of top of Pittsburgh Coalbed at lines 1 and 2, constructed from interpreted seismic reflection data.

observation. Figure 8 is a depth cross section of line 1. It was constructed from the time record using downhole velocities obtained from the Gateway No. 1 test hole. This section shows the washed-out coalbed at shot point 61, as well as interpreted faults.

Fault interpretation is based on reflection offset. The minimum, frequency controlled, offset resolution is 10 ft. Interpreted fault offsets along lines 1 and 2 are on the order of 10 ft, just at the limit of resolution. Underground experience in the area shows offsets to be around 2 to 5 ft, but offsets of 10 ft are known in channel slump features. The only way to evaluate a fault interpretation would be to drill immediately on

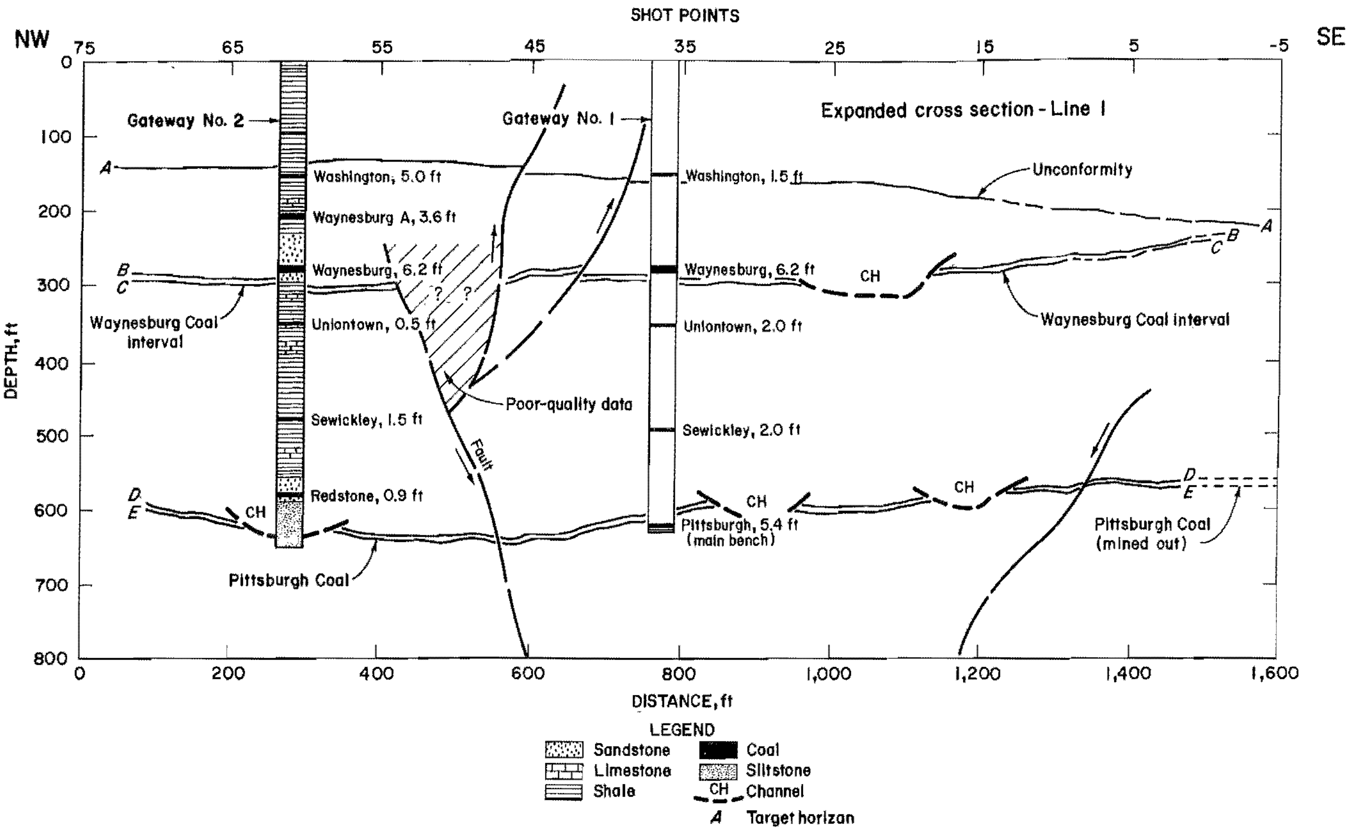

FIGURE 8.—Cross section of line 1 showing structure interpreted seismic reflection data.

either side of the fault plane and measure offsets, or to map the area immediately after mine-through. In this case mining was not considered owing to the known presence of a want.

The faults interpreted for shotpoints 45-55 are drawn to extend between the Waynesburg and Pittsburgh horizons. This type of major structure is rare in the area. More likely these offsets are local depositional slump blocks common to coal measures that are intersected by paleochannels and do not extend between coalbeds. This is a situation where knowledge of local structure and coalbed geology would aid in the interpretation.

The accurate contouring of coalbed thickness was determined to be unreliable based on the quality of data available. To measure coalbed thickness, distinct reflections of both the top and bottom of the seam must be resolved. The data being recorded at that depth are not of high enough frequency to separate the top and bottom horizons. Therefore, the use of this seismic method for mapping coalbed thickness in this situation is not possible using the interpretive methods available at this time.

The mapping of local structural trends was an objective of the seismic reflection technique. Though somewhat inconsistent, the results show that structural elevation can be successfully predicted. Table 1 compares the variation of predicted seismic lithologic tops from lines 1 and 2 with actual log data. It can be seen that the predicted structural tops of the Pittsburgh horizon vary by as much as 21 ft from the actual top location. For example, in borehole GD-55 the elevation of the top of the Pittsburgh Coalbed from the borehole log is 375 ft. The predicted elevation from seismic interpretation is 373 ft. The variation in top elevation is 2 ft. In boreholes GD-55, JLF-41, and Gateway No. 1 the Pittsburgh top prediction was reasonably

TABLE 1. - Variation of seismic interpretation from actual log data, lines 1 and 2

Borehole	Pittsburgh top (elevation above sea level), ft		Variation, ft
	Log	Seismic	
GD-6	373	352	21
GD-55	375	373	2
GD-101	383	392	9
Gateway No. 1	372	376	4
Gateway No. 2	Washout	Washout	0
Gateway No. 3	381	Washout	NA
JFL-41	377	374	3
JA-1	384	369	15

NA Not available.

accurate, but in the Gateway No. 2 test hole the channel washout was exactly predicted.

Figure 9 is the fully processed, interpreted seismic record for line 2. The same three target horizons (A, B-C, D-E)

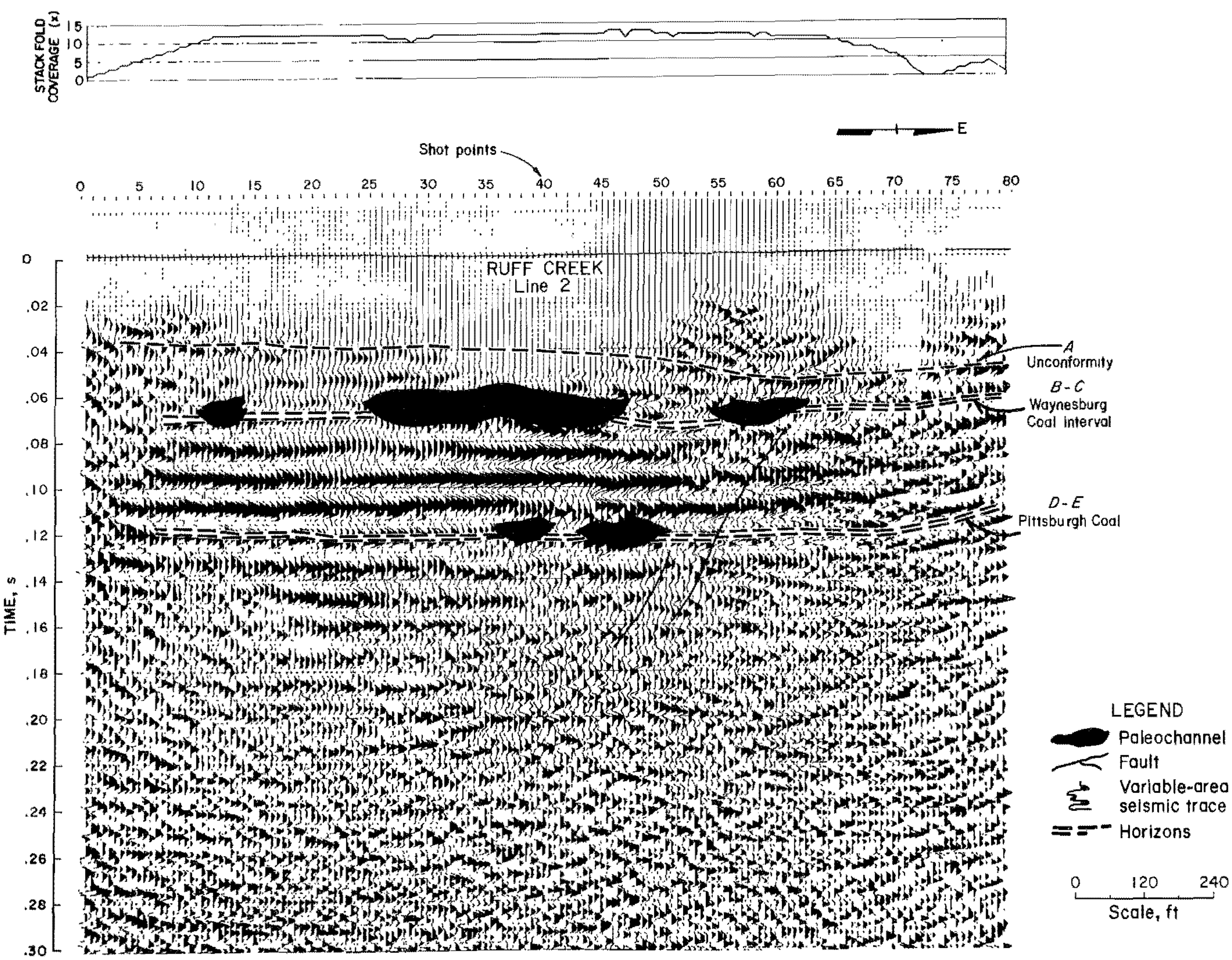

FIGURE 9.—Processed interpreted seismic record for line 2.

are indicated. Interpreted paleochannels include Pittsburgh horizon shot points 38 and 47, Waynesburg horizon shot point 11, shot points 25-47, and shot point 58. Faulting is interpreted through the Pittsburgh horizon at shot point 56.

On line 2 an interpreted paleochannel located in the Pittsburgh Coalbed at shot point 38 was also tested by drilling (Gateway No. 3) (fig. 10). In this case an entire section of Pittsburgh Coalbed sequence was encountered. While this situation shows an obvious failure to seismically predict the paleochannel, some of the coalbed properties are interesting. The coal core was vertically fractured and otherwise distorted with slickensides. This caused rotation of the core in the core barrel and the loss of 3.4 ft of coal. This type of disturbance is common in coal adjacent to or on the margins of paleochannels. Thus, it is possible that a paleochannel is nearby.

Other existing exploration holes were located on or near predicted paleochannels along lines 1 and 2 (fig. 7). Borehole GD-7 is located on the margin of a predicted paleochannel and shows only 2.4 ft of coal. Hole GD-8 is located directly in the paleochannel trend and shows 3.8 ft of Pittsburgh Coal. These are encouraging results. Both holes indicate the location of thinning trends within predicted washout areas, but hole J-10 shows 6.5 ft of coal directly within the predicted channel trend. This could be the result of error in predicting the trend of the meandering channel. A shift of only a few degrees in either direction could move the interpreted channel away from hole J-10.

Figure 11 is a conceptual drawing of the want area at lines 1 and 2. It was constructed from interpreted seismic data from lines 1 and 2. This interpretation of the processed seismic record shows a bifurcating channel and another channel meander in their spatial relationship to the mined-out areas. Small-scale faulting is also shown. This is the type of information desired from seismic survey.

Other discontinuities identified seismically on line 1 include a washout at the Waynesburg interval from shot point 17 to shot point 27 (approximately 200 ft wide). Although not directly tested, it is known that in the study area the Waynesburg Coalbed has a consistent lithology. Therefore any individual washout of Waynesburg coal is probably misinterpreted.

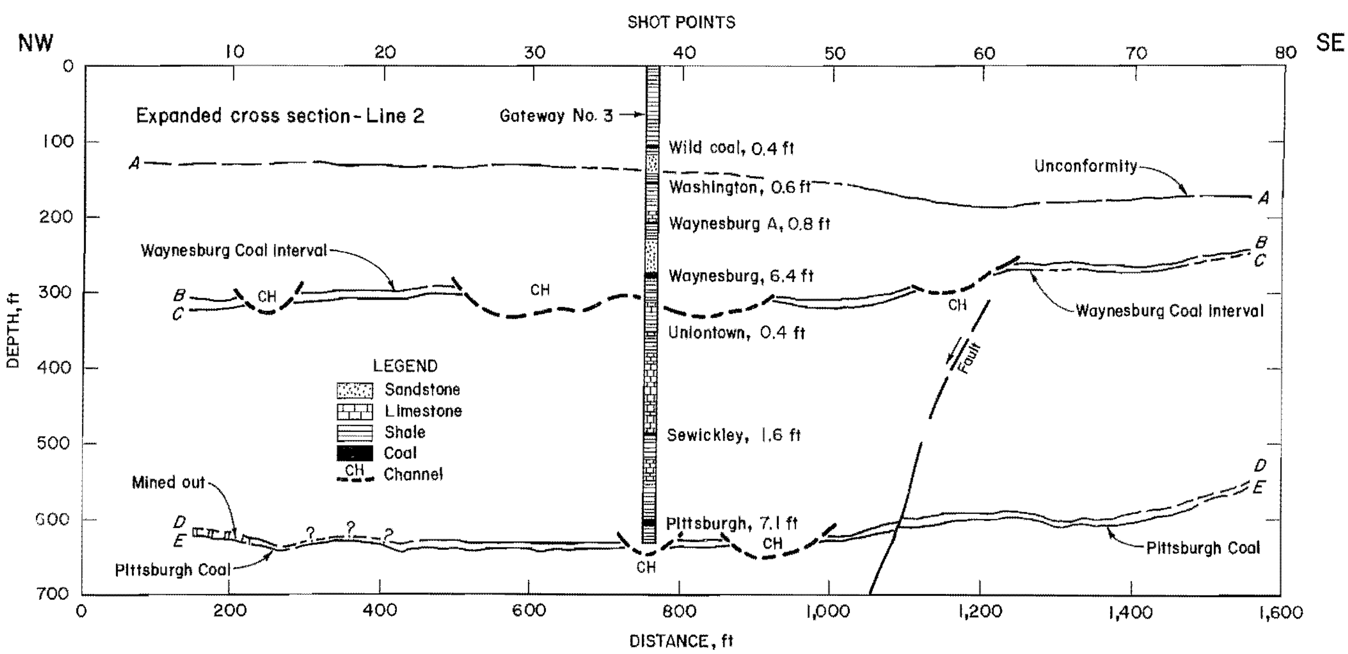

FIGURE 10.—Cross section of line 2 showing structure interpreted from seismic reflection data.

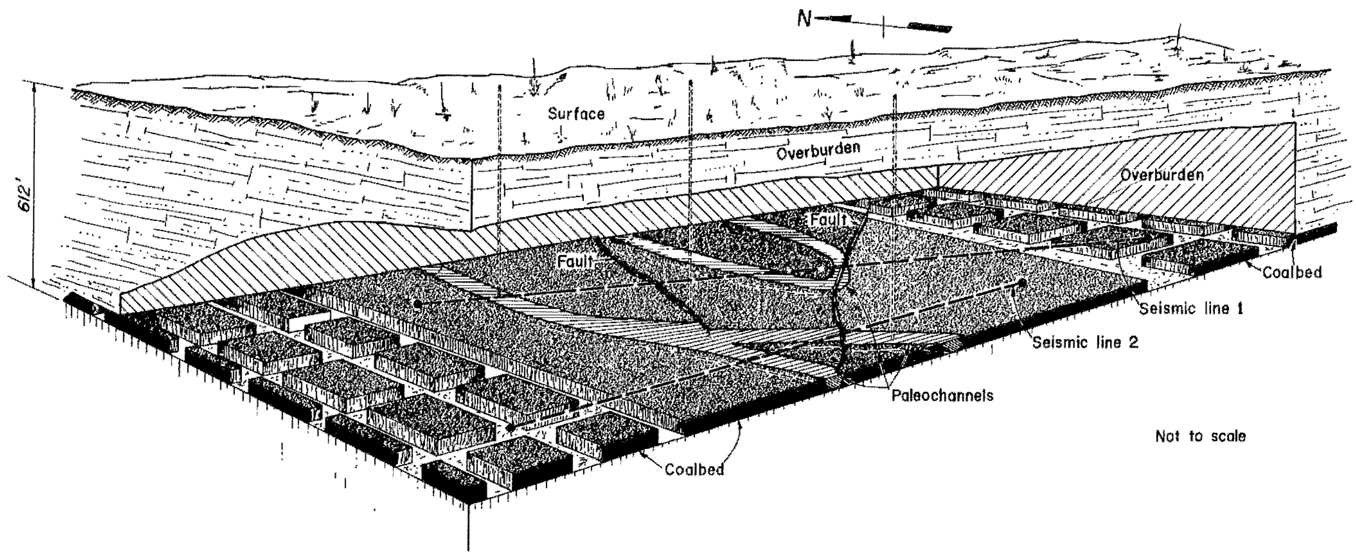

FIGURE 11.—Conceptual drawing of subsurface at lines 1 and 2 constructed from seismic reflection data.

Between shot points 47 and 54 on line 1, the quality of the data breaks down. The prominent Waynesburg banding disappears. Possibly dispersed energy from the adjacent slump blocks is attenuating the signal in this area.

Horizon A was tracked on all four lines because of the unusual convergence of reflector bands. This situation has been interpreted as representing an unconformity. Convergence of this horizon with the Lower Waynesburg Coalbed is seen on all four time-distance sections. It is estimated from this unconformity that 80 to 100 ft of stratigraphic section is missing from the Pittsburgh-Waynesburg interval. Convergence of horizons A and B-C generally occurs to the east and northeast on line 3 (fig. 12). Additionally, on line 3, there appears to be an interpreted sharp truncation of the Waynesburg interval by horizon A at shot point 91. As mentioned above, the Waynesburg Coalbed is almost always present. Drill hole GD-62, located approximately 800 ft from the truncation of line 3, confirms this, showing over 6 ft of Waynesburg coal. Though no other evidence of this unconformity exists, the reflector convergence still indicates this type of structure.

The portion of line 1 east of shot point 1 extends over a mined-out area. The presence of the mine should be seen in the seismic record. Figure 6 is seismic record from line 1 and shows the termination of the D-E reflector (Pittsburgh Coalbed) right at the mine boundary. This correlation is encouraging. Line 2 extends over the mine on its western extension (west of shot point 11). In this case the strong Pittsburgh Coalbed reflector extends past the mine boundary, whereas, in theory this reflector ought to deteriorate owing to reverberation of incident energy in the mine.

LINE 3 RESULTS

Line 3 is located approximately 1/2 mile south of the West Main development of the Gateway Mine (fig. 4). It is 2,360 ft long and was shot on the side of a hill roughly parallel to the topographic contours along the valley wall. This line was located in a suspected want area in virgin coal. Figure 12 is the processed seismic section, and Figure 13 is the interpreted depth cross section. The overall quality of field records obtained on line 3 was better than that obtained on either line 1 or 2; this is attributed primarily to better signal transmission through higher velocity near-surface bedrock layers present along the profile. Eight major faults are interpreted to explain offsets on both the Waynesburg and Pittsburgh

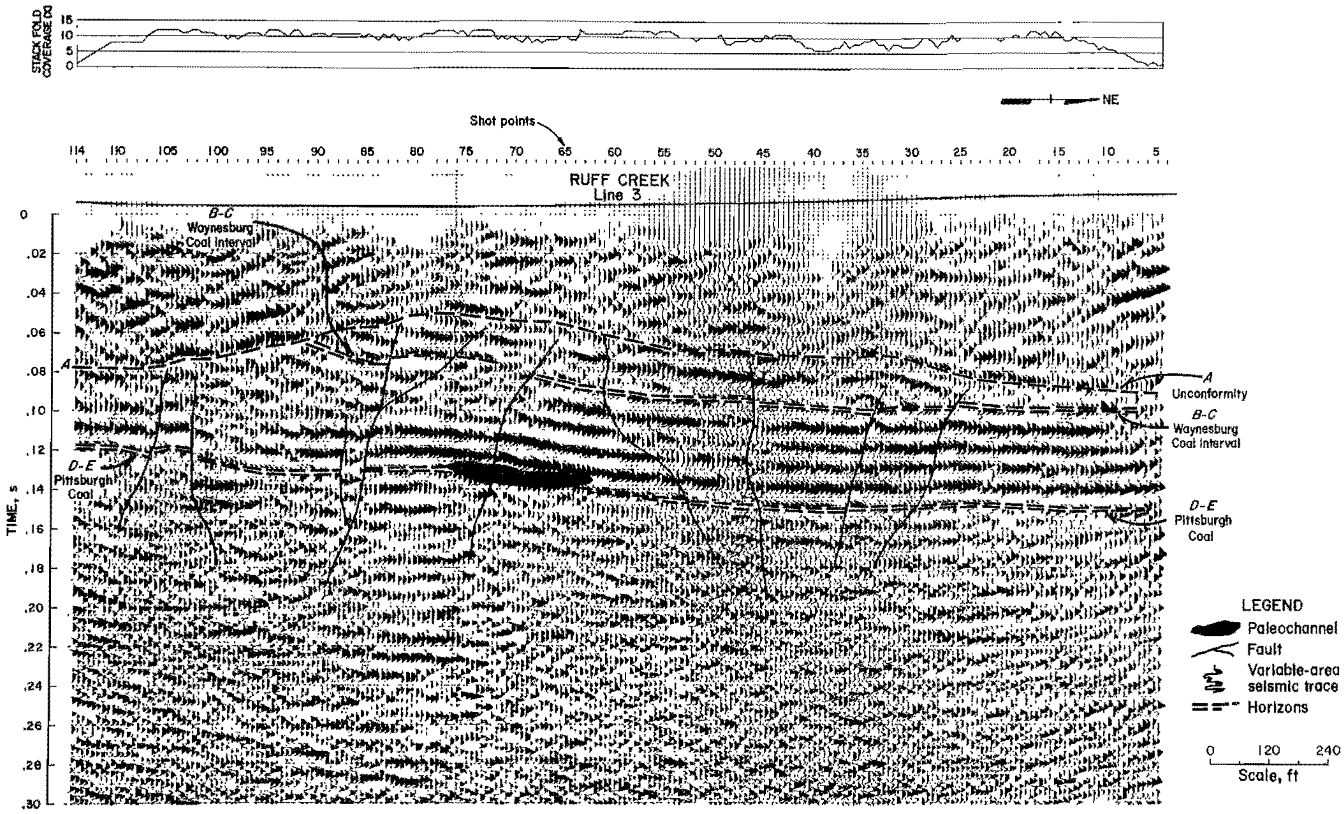

FIGURE 12.—Processed interpreted seismic record for line 3.

horizons. This type of major structure does not occur in the area, and the offsets are most likely local slump block faults and not correlatable between horizons.

Four exploration coreholes provide control data to test the interpreted seismic horizons (fig. 14); table 2 lists the comparison of actual logged horizons with interpreted seismic horizons for three of the holes. The remaining borehole, GD-71, is located outside the area of influence considered reasonable for seismic interpertation. Although the Pittsburgh horizon was picked 7 ft lower than it actually is in borehole GD-69, borehole GD-70 confirms the seismic interpretation. Borehole GD-70 is located exactly in the interpreted paleochannel and shows no trace of the Pittsburgh Coalbed. Borehole GD-61 is located on the margin of the interpreted channel and shows only 3.5 ft of the Pittsburgh Coalbed. But if the trend of the interpreted paleochannel is turned to the west, which is reasonable since only one dimension can be assumed by line 3, then this borehole would also fall within the channel margins and would be considered a successful test. The variation between seismic interpretation and log data in the Waynesburg horizon is even greater, probably owing to lack of calibration velocity data.

TABLE 2. - Variation of seismic interpretation from actual log data, line 3

Borehole	Top (elevation above sea level), ft: Log	Top (elevation above sea level), ft: Seismic	Variation, ft
WAYNESBURG			
GD-61....	679	730	51
GD-69....	683	678	5
GD-70....	684	722	38
PITTSBURGH			
GD-61....	362	Washout	NAp
GD-69....	354	347	7
GD-70....	Washout	Washout	0

NAp Not applicable.

On the southwest end of line 3, the seismic data indicate a marked rise in

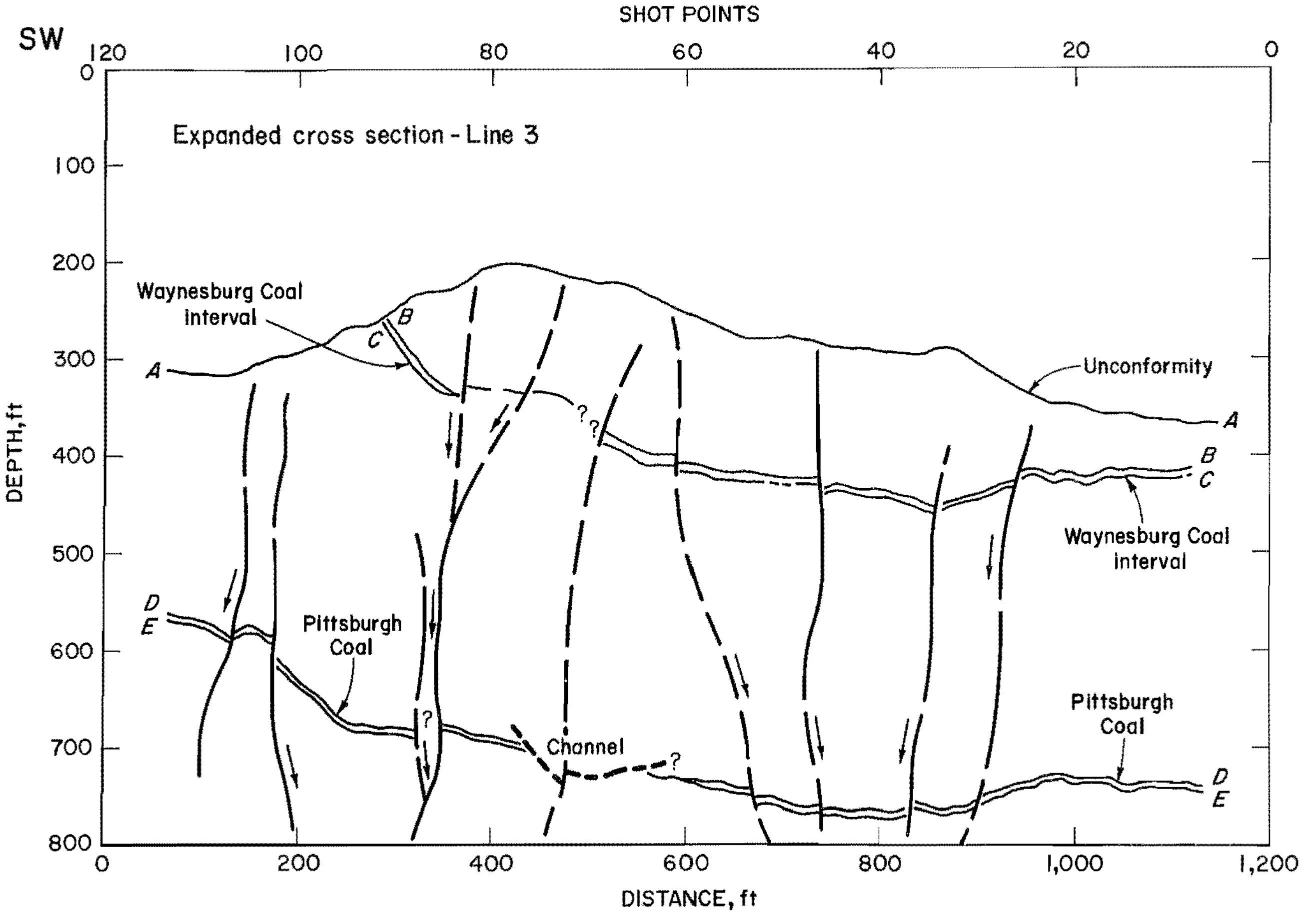

FIGURE 13.—Cross section of line 3 showing structure interpeted from seismic reflection data.

elevation of both the Pittsburgh and Waynesburg horizons (figs. 12 and 13). A total elevation change of over 200 ft in approximately a quarter mile is indicated. This degree of structural change is unknown in this region and is most definitely in error.

A paleochannel is indicated at shot points 65–72. Downbowing and cycle splitting of the reflector are the interpretation criteria.

LINE 4 RESULTS

Line 4 is located approximately 1 mile northwest of lines 1 and 2 (fig. 5). It is 2,600 ft long and was shot along a State highway with medium-light traffic. Field conditions and recording conditions were generally fair to poor, and there were three gaps of four- or five-station intervals where geophones or shots could not be employed across access roads and a utility pipeline. At many line stations the detectors could not be buried or planted securely owing to extended patches of hard roadbed gravel or compacted soil, resulting in a very low seismic signal-to-noise ratio. Consequently, the data from line 4 are of lower quality than earlier data, and therefore are not presented.

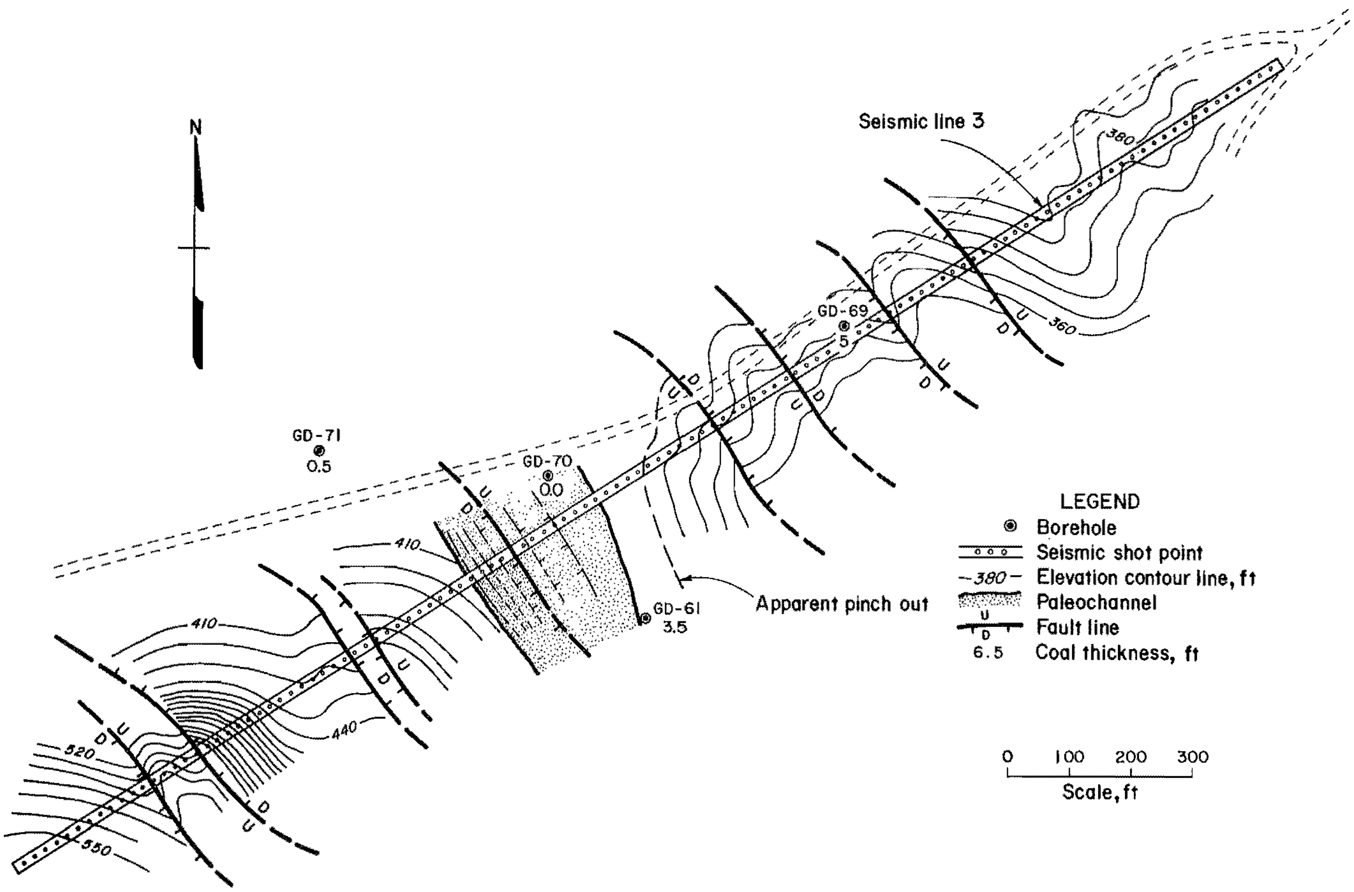

FIGURE 14.—Structure contour map of top of Pittsburgh Coalbed at line 3, constructed from seismic reflection data.

EVALUATION OF THE EFFECTIVENESS OF HIGH-RESOLUTION SEISMIC REFLECTION FOR COALBED EXPLORATION

COALBED THICKNESS

The mapping of coalbed thickness by seismic reflection at the Gateway study area has been shown to be unreliable. The average thickness of the Pittsburgh Coalbed at the Gateway Mine is approximately 5.2 ft. For accurate resolution of both the top and bottom horizon reflections, given the same quality of data, the coal height would need to be a minimum of 10 ft. It is estimated that 1,000 Hz return energy would be needed to achieve the desired resolution (5.0 ft).

FAULTING OFFSET

Fault offsets on lines 1 and 2 are 5 to 10 ft. There are two interpreted faults at the Pittsburgh Coalbed horizon and three interpreted faults at the Waynesburg Coalbed horizon on the processed record of line 1 (fig. 6). This amount of offset is very near the level of resolution, so interpretations are difficult. But it appears possible that local offsets of this magnitude can occur around the margins of paleochannels (4). Underground mapping has confirmed the existence of slump blocks along channel margins, and these faults may be interpreted as such. The interpretation of faults to extend several hundred feet between coalbeds (figs. 6 and 12) appears to be unlikely. On line 2, faulting is indicated only at shot points 55 and 52. Interpretation criteria are indirect and include vestigial diffraction events and migrated seismic noise.

On line 3, eight faults are interpreted to interrupt the sequence (fig. 12). All of the faults appear to die out below the interpreted unconformity (horizon A). The faults may still be related to the one predicted channel (shotpoints 62-77), but the predicted offsets of 10 to 30 ft are considered large for local slump blocks. That the faults are continuous through the Waynesburg Coalbed is considered unlikely. It is possible that offsets occur independently in the Waynesburg Coalbed, and this may well be the more accurate interpretation.

Reflector offsets are the most obvious interpretation criteria for faults. Cycle splitting and deterioration of return signal may also be important, but differentiating between these events and unrelated noise is difficult. Resolution of small-scale offsets (<10 ft) is still unreliable.

DISCONTINUITY

The identification of coalbed discontinuities was a major objective of the project. Paleochannels were identified, and two were proven by test drilling. Consistent identification of these structures is thought to be an achievable goal. An interpreted discontinuity was confirmed by the Gateway 2 test hole on line 1. On lines 1 and 2, several boreholes indicated thin coal in a seismically predicted discontinuity. Although not completely accurate, this indicates a channel in the vicinity and that the problem with horizontal resolution needs attention. On line 3, a paleochannel washout was correctly predicted seismically, as proven with an existing exploration hole. A necessary improvement in application would be the identification of channels in the roof, that do not intersect the coalbed. Identifying such channels would be more difficult since termination or downbowing of the strong coal reflector is the primary criterion for discontinuity, and neither of these events would occur if the coal seam were not intersected. A modeling study of synthetic seismic response to specific types of discontinuities to establish a set of interpretation criteria would make interpretation much more reliable. Although it is difficult to determine the extent to which the coalbed is interrupted, the detection of this type of discontinuity (paleochannel) appears to be the most successful part of the seismic reflection mapping study. Interpretation of the endpoints of discontinuities is estimated at between one and two surface station intervals (20 to 40 ft).

COALBED ROLLS

The mapping of structural trends, another objective, was hindered by the need for more velocity calibration data. Although in a number of instances the tops of target horizons were successfully mapped, there is a need for more consistency in predicting target depths. Of 11 test cases in which borehole control was available, 5 were considered to be reasonably accurate interpretations of coalbed elevation.

QUALITY OF SEISMIC DATA

Lines 1 and 2 were located at the bottom of the Ruff Creek valley. An average of about 10 ft of alluvium fills the valley and posed a problem to energy transmission. Low velocities from the unconsolidated deposits caused attenuated signals and contributed to lesser quality data. One solution would be to drill shot holes to consolidated material to allow a better chance for deep energy transmission. In addition these holes will help reduce unwanted airwaves and also ground roll, which tends to swamp returning signals.

Data from line 3 were probably of the highest quality of all the lines. Since line 3 was located on a hillside, unconsolidated material consisted of weathered bedrock. Average velocities for this material are higher than for valley fill and allow better energy transmission. Although there data were of better quality than the data for lines 1 and 2, lack of calibration information made some interpretations suspect. Overall, the quality of data is considered fair.

IMPROVEMENTS IN THE QUALITY OF ACQUIRED DATA

A number of practices may help to improve the quality of data gathered or provide the kind of information necessary to improve interpretation of the processed seismic data. For accurate seismic mapping, a basic grid network of seismic lines is required. Single profiles are often inadequate, especially if the separation between profiles is large. A grid of some form yields both strike and dip information as well as the very important element of being able to tie the interpreted horizons in a closed network similar to that used in conventional surface surveying.

A square grid over a prospect area with at least two corehole control points at either end tied to two profiles each would be an optimum layout; such a layout is shown in figure 15*A*. A less ideal but still acceptable grid could be done in some form and tied to boreholes along a single profile such as is shown in figure 15*B*. A more probable layout, considering access and terrain, would more likely be similar to that shown in figure 15*C*; such a layout is acceptable if the borehole offsets to the profiles are not too great.

The point to be emphasized is that all seismic lines should be tied, and as much borehole control as practical should be integrated within the network so that common-depth-point seismic velocities along each profile can be adjusted over the network to yield more accurate depth estimates.

Calibration holes are critical to accurate interpretation. Gateway No. 1 was drilled specifically for this purpose between lines 1 and 2. The subsequent interpretations were more accurate than those for lines 3 and 4, where no velocity or density information was available.

All calibration boreholes should be drilled past the Pittsburgh Coalbed interval at least 20 to 30 ft so that the underlying rock unit velocities can be obtained. Sonic logs with an integrated time trace should be run in each borehole and carefully edited to eliminate cycle skips and spurious velocities.

One problem that surfaced early in the study was in the interpretation of recorded reflections. There is a need to model accurately the seismic response to actual materials, like the silt and sandstone that fill paleochannels. Duffy (5) generated seismic responses to synthetic materials that simulated channel fill. A sequence of synthetic seismogram calibration model profiles should be produced showing a variety of geologic features. These include thin sandstone and coal lenses, eroded channels of various widths and depths, faulting at various depths and with different amounts of displacement, and various thicknesses of typical coalbed units and surrounding strata to define resolution limits. A modeling study is a key element in establishing a set of recognition criteria involving definition of seismic stratigraphy.

Since it appears that local lithology, surface fill, and weathered layers are important in the transmission of incident energy, it is a good idea to test the

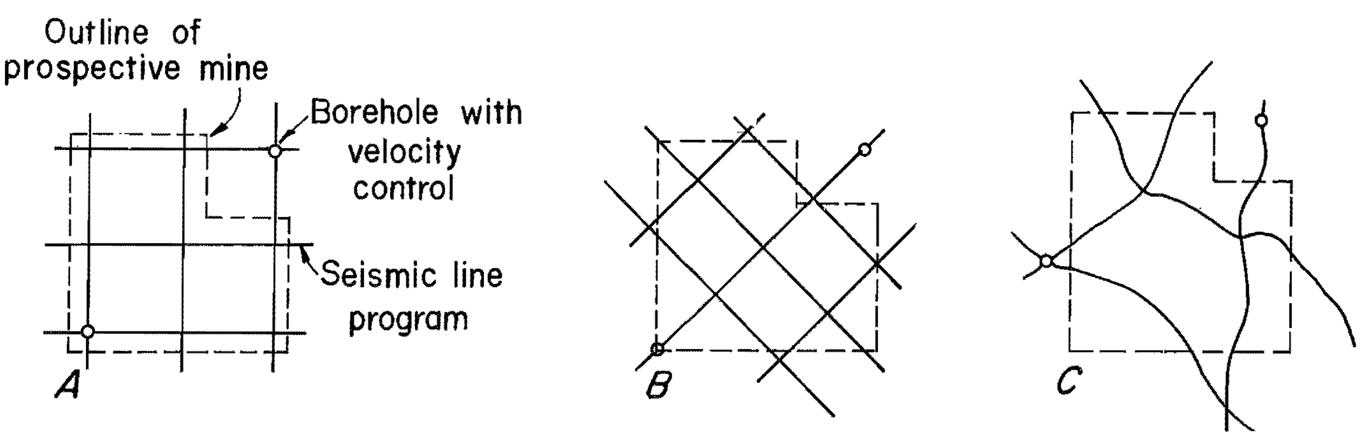

FIGURE 15.—Possible field geometries for seismic reflection programs.

transmission properties of rock before the actual production survey. By setting test shots from within the mine to be detected at the surface, one can determine both the dominant frequency received and to what degree the signal will be impeded. This variation of the downhole seismic reference test can aid in evaluating the probability of a successful seismic survey.

EFFECTIVENESS OF EXPLORATORY DRILLING FOR DELINEATING A PALEOCHANNEL SYSTEM

Exploratory drilling on a coal property is generally conducted in phases. The first phase usually consists of widely spaced (3- to 4-mile centers) test holes, which are used to conform the regional presence of coal on the property and its quality. These holes are the initial evaluation points, and data from them may influence the decision to purchase and develop the property. The next phase would consist of infilling the wide pattern in the area where mining is to be started. If thin or absent coal is encountered, then closely spaced test holes (1,000-ft centers) may be drilled in an attempt to delineate the want area. Figures 16 through 18 show the chronological progression of exploration and developmental data available in the study area through time. Figure 16 is an isopach map of Pittsburgh Coalbed thickness in the study area prior to mining. There are 30 test holes over the 11.5-mi^2 study area, drilled on roughly 3,200-ft centers. These data indicate four areas of thin or absent coal. Two of these wants are indicated by only one borehole, one is indicated by two holes, and one is indicated by four holes. With only these data, the ability to delineate the size, shape, or trend of the want areas is greatly diminished.

Figure 17 is a Pittsburgh Coalbed isopach map based on additional borehole information and mine surveys. All subsurface information up until 1976 has been considered. A total of 38 boreholes and 72 mine survey points provide data for mine planning. The new information actually provides little additional resolution of the geometries of known want areas. The West Mains development is approaching an area of thin coal. With only the sparse borehole information available at that time, there was no way to determine the extent of the discontinuity. Subsequently, the development was halted and turned south around the discontinuity.

Three coreholes in the northwest quadrant of the study area show two potential want areas (fig. 17). With only this information, conventional contouring methods will represent these areas as large pods with no detail at all. Efficient development of these areas will require a much denser borehole exploration program.

Figure 5 is a coal isopach map constructed from all available conventional subsurface information up to the present time. This information includes 107 boreholes and 269 mine survey points and measured sections. From this map, the size and complexity of the channel system in the west mains and 8 face area can be seen. The sand- and silt-filled paleochannels enter and exit the coalbed from the roof in a random manner. In addition, coal adjacent to the margin of the stream channel deposit locally reaches a thickness of over 7 ft. This type of detail is impossible to obtain with conventional exploration no matter how dense the drilling grid. In contrast, the large isopached pods of thin coal in advance of mining remain featureless. It is almost certain that they are as complex as the mapped system.

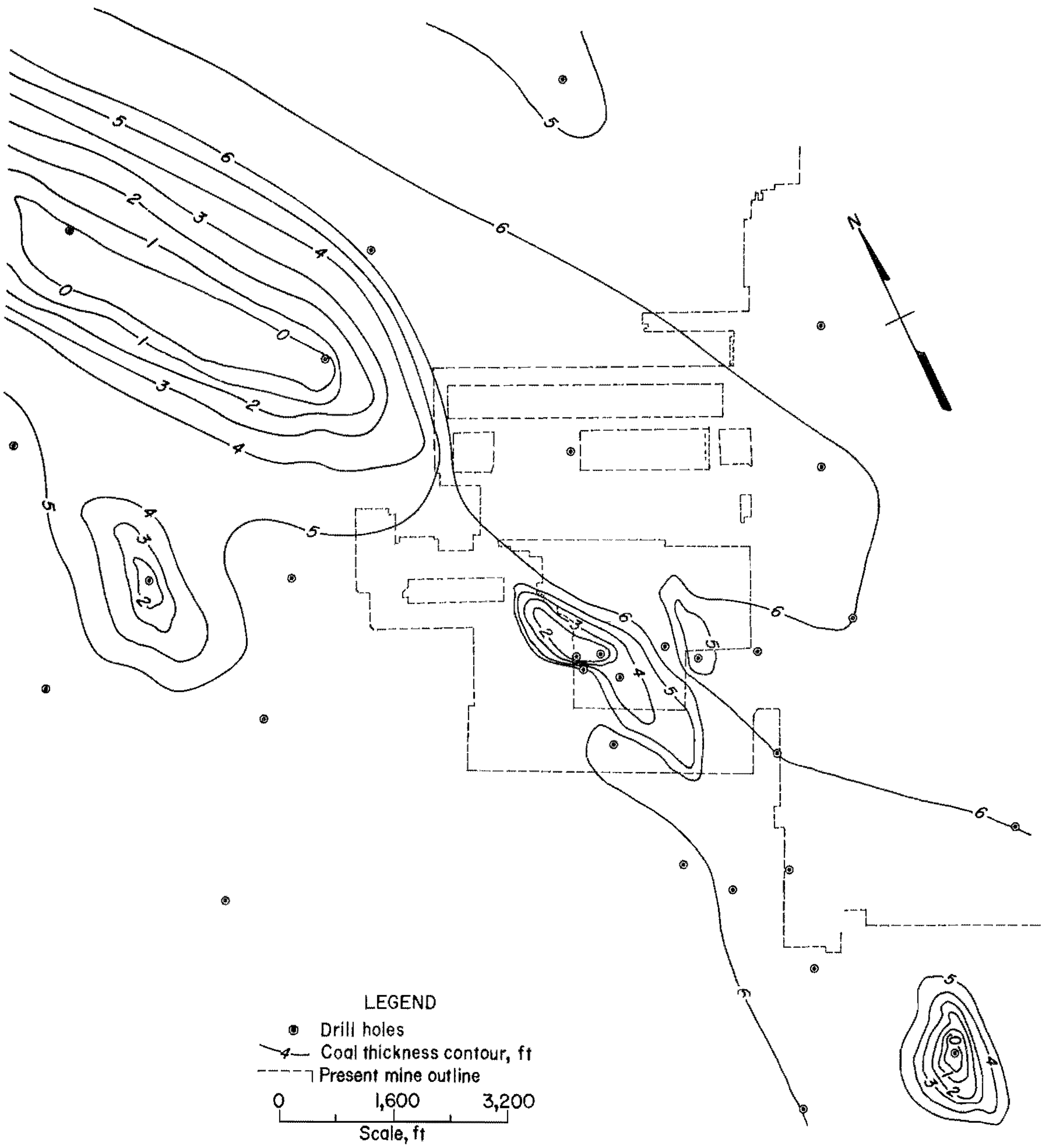

FIGURE 16.—Isopach map of Pittsburgh Coalbed in study area prior to mining (drill holes up to 1972).

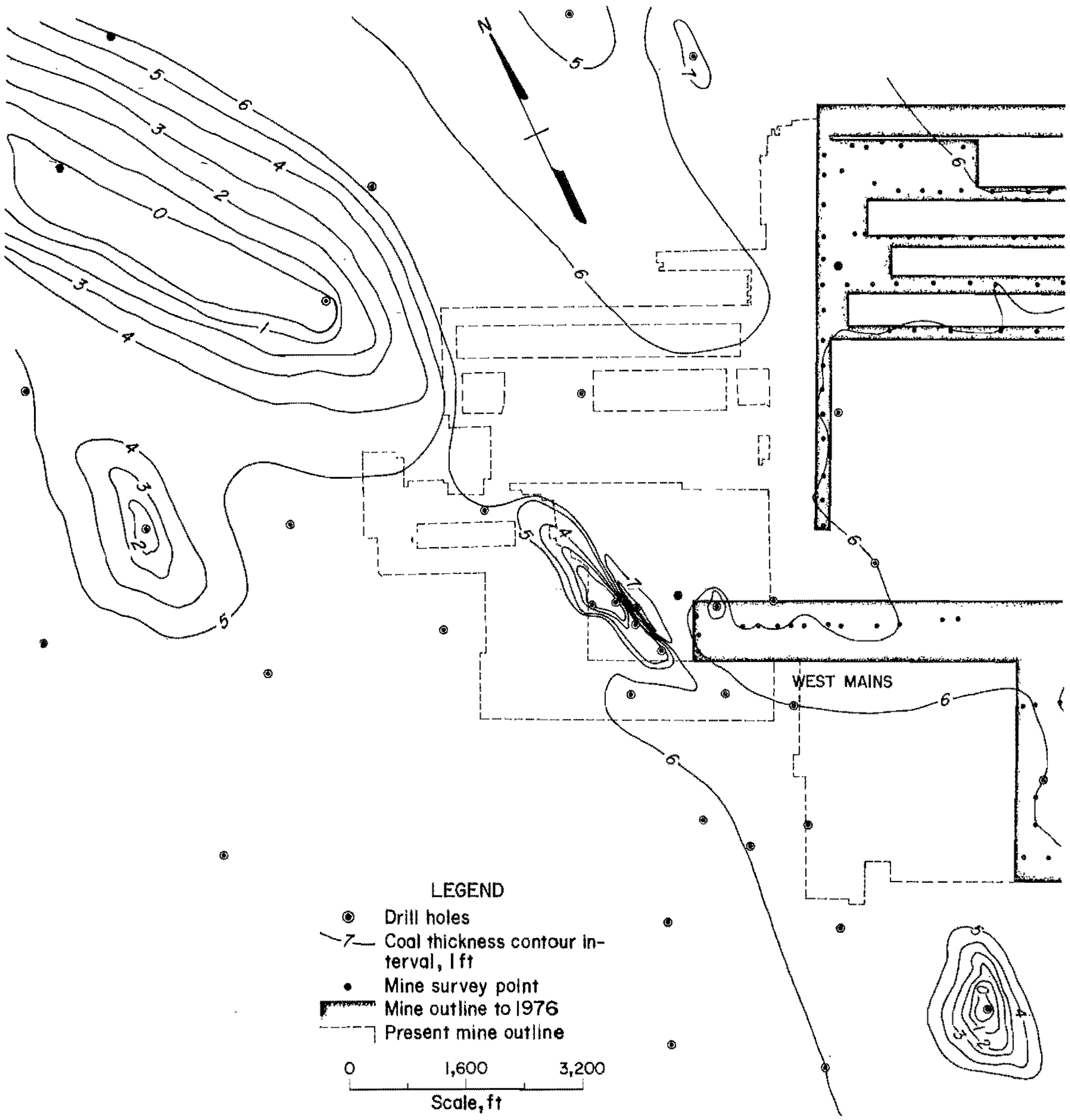

FIGURE 17.—Isopach map of Pittsburgh Coalbed during past mining activity (drill holes and mine survey points up to 1976).

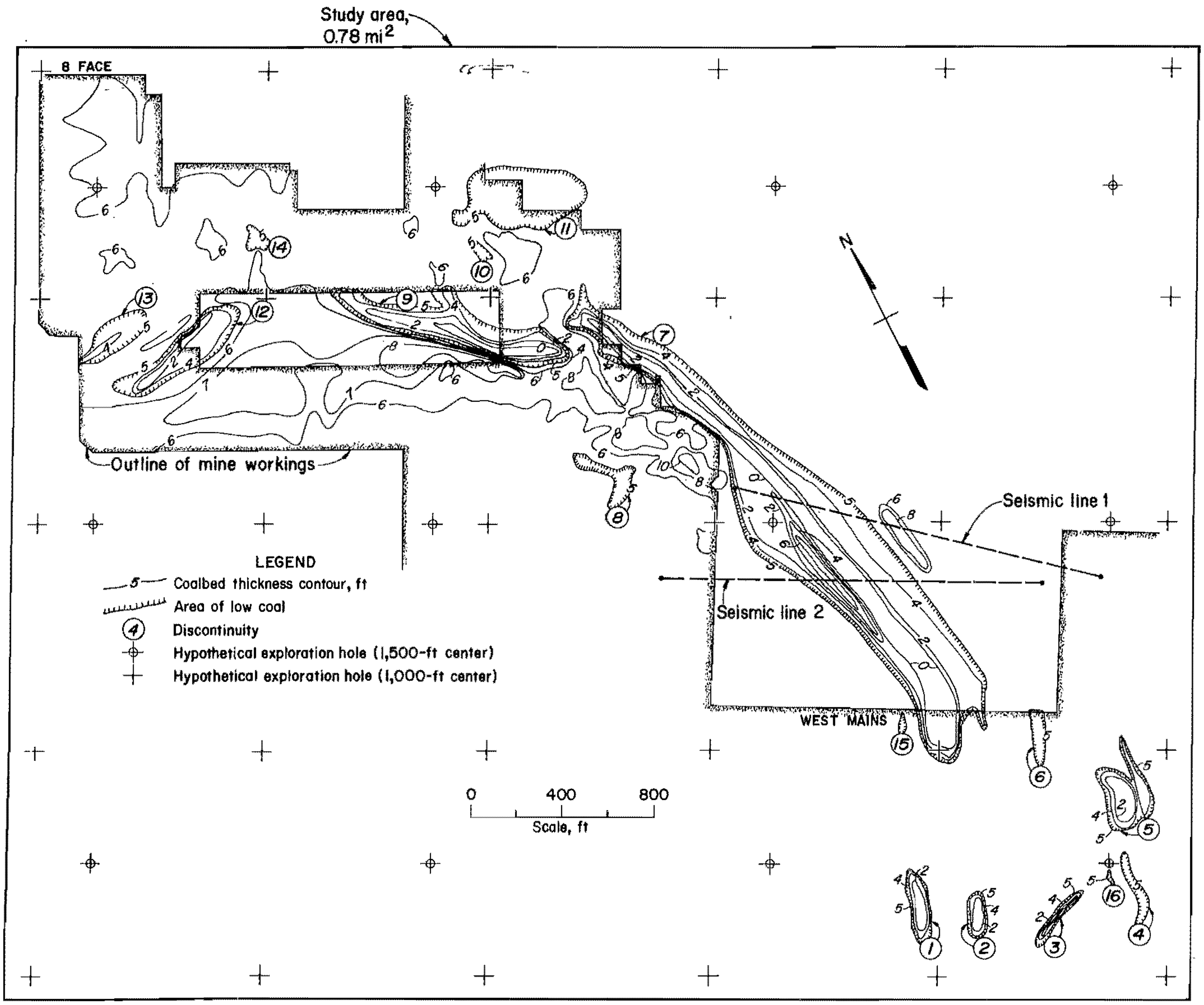

FIGURE 18.—Isopach map of Pittsburgh Coalbed in the 8 Face area with referenced discontinuities and hypothetical borehole grids.

PROBABILITY OF ENCOUNTERING COALBED DISCONTINUITIES AT GATEWAY MINE

Houseknecht (6) has discussed a method for estimating the probability of encountering coalbed discontinuities in virgin coal based on their size, shape, and orientation. Probabilities are calculated for different borehole spacings and grid patterns. The technique assumes a certain amount of control data. Given the borehole information and mine surveys available at the Gateway Mine, it is possible to characterize the size, shape, and orientation of known discontinuities. The assumption is that the same physical properties of discontinuities will occur over the rest of the unexplored property, and that the occurrence of discontinuities can be predicted given certain borehole spacings.

Discontinuities in the 8-Face area of the Gateway Mine are defined as any area in which the coal height (Pittsburgh Coals, main bench) is under 5 ft. Coal height under 5 ft is considered low for this area and can cause roof control problems as well as low production.

An area of 0.78 mi^2 was outlined within the study area. Underground observation and borehole information identified 16 discontinuities based on the criteria stated above (fig. 18). The total area of the 16 discontinuities is 0.04 mi^2, accounting for approximately 5 pct of the outlined area. Two hypothetical borehole grids were overlain on the smaller study area (fig. 18). At a spacing of 1,000 ft only 1 of 30 test holes encountered a discontinuity, or about a 3-pct success rate. Actual boreholes drilled in the discontinuity area showed 5 out of 16 holes encountered 5 ft or less of coal, or a 31-pct success rate. This rather high success rate was biased because holes were being targeted for known areas of discontinuity. Boreholes were located in an attempt to delineate the want based on the previous borehole encounter.

The technique for estimating the probability of encountering discontinuities has been applied to the Gateway Mine property. For each numbered discontinuity, table 3 indicates the borehole spacing that would be necessary in order to be 100 pct, 85 pct, and 75 pct certain of hitting the specific discontinuity with an exploration test hole. For example, if discontinuity 9 were selected, in order to be 100 pct certain of detecting this 1,100- by 250-ft N 48° W oriented discontinuity, with a designated shape factor of 0.2, test holes would need to be spaced 463 ft apart. As the confidence level is reduced, the associated minimum borehole spacing is increased, as indicated in the table. It is unrealistic to expect primary exploration drilling grids to space holes on 463-ft centers, as would be necessary to detect discontinuity 9. Not only would this practice be uneconomical, it would probably present property access problems as well.

At the borehole spacing used by the mine for exploration (1,500-ft centers), only the longest discontinuity would have been detected and then at only one point (No. 7, 2,625 ft long). It becomes obvious that the paleochannel system that has seriously affected coalbed thickness in the study area would have little chance of being adequately delineated by a conventional borehole grid.

TABLE 3. - Borehole spacing related to probability of discontinuity detection, Gateway Mine study area

Discontinuity[1]	A-axis length, ft	B-axis length, ft	Orientation	Shape factor $\left(\frac{\text{B-axis}}{\text{A-axis}}\right)$	Borehole spacing, ft, necessary to achieve given probability (P) of encountering discontinuity		
					P = 100 pct	P = 85 pct	P = 75 pct
1.......	330	100	N 19° E	0.3	203	240	252
2.......	200	85	N 21° E	.4	132	178	200
3.......	320	55	N 62° E	.2	183	214	232
4.......	323	75	N 11° E	.2	136	161	185
5.......	400	217	N 8° E	.5	291	356	400
6.......	245	75	N 24° E	.3	163	196	228
7.......	2,625	433	N 18° W	.2	1,312	1,616	1,750
8.......	315	194	N 13° W	.6	280	376	360
9.......	1,100	250	N 48° W	.2	463	587	629
10......	110	55	N 25° W	.5	185	220	251
11......	590	225	N 60° W	.4	392	556	590
12......	640	180	N 77° E	.3	342	427	466
13......	435	140	N 81° E	.3	218	268	290
14......	130	90	N 23° W	.7	192	236	256
15......	95	37	N 19° W	.4	64	80	92
16......	75	25	N 0°	.3	34	40	46

[1]Locations shown in figure 8.

CONCLUSIONS

High-resolution seismic reflection was most successful in delineating paleochannel discontinuities. In several cases, boreholes confirmed the existence of interpreted channel washouts. Fault offsets of 5 to 10 ft on lines 1 and 2 are considered reasonable, although difficult to confirm. Fault offsets of 10 to 30 ft on lines 3 and 4 are less reliable. The questionable interpretation of *large* structural changes in the target horizon elevation along lines 3 and 4 is attributed to the lack of velocity calibration data; however, *locally*, the elevations of the objective reflectors were reasonably predicted in 5 of 11 cases.

The mapping of coalbed thickness was unsuccessful. Higher frequency return signals are needed to resolve both top and bottom of a 5- to 6-ft coalbed.

Interpretation of processed records appears to be a significant problem. Lack of experience in this area could be corrected by modeling experiments. Other improvements, such as better field geometries for seismic lines, adequate borehole calibration data, and improved transmission of incident energy, may help produce a better final product.

The ideal use for seismic reflection is to provide developmental data. If borehole information and underground observation indicate the approach to a want area, then several well-placed seismic lines may be more effective and economical than a large number of boreholes.

A total of 107 exploration holes, averaging 800 ft deep, have been drilled on the Gateway Mine property. At the current rate of $12/ft for core drilling, over $1 million has been spent for exploration. Adding approximately $1,000 per site for mobilization and demobilization, site preparation, and cleanup, the cost approaches $1,200,000. It is acknowledged that exploration coreholes are a necessity to property evaluation. The need for a physical sample of coal and roof and floor rock for chemical and physical analyses will always remain. But it is suggested that a mix of drilling data and seismic reflection coverage can provide more information than either exploration technique can provide alone.

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APPENDIX.--DATA ACQUISITION AND PROCESSING PROCEDURES

ACQUISITION SPECIFICATIONS

The following equipment and field procedures were used:

Mapco 21-mm Seisgun as the energy source

DHR 1632 instruments for recording

48 record channels

1/4-ms sample rate

1.5-s record length

Geophones with 40-Hz standard frequency

Geophones spaced at 20-ft intervals

Single geophones

Shot point intervals of 20 ft

Subsurface data points every 10 ft

End-on 20-ft offset profiles

12-fold CDP stack

FIELD PROCEDURES

The initial field work in the project area began on line 1 and consisted of determining the local seismic properties of ground roll, thickness of the low-velocity weathered layer, ambient noise level, and energy transmission.

A low-cut filter setting of 90 Hz on the seismic amplifiers eliminated the low-frequency fan motor noise, and planting the geophones deeply into the soft soil, as well as covering the lead-in cables of the detectors, virtually eliminated high-frequency wind noise. Road traffic and drill motor noise was avoided by shooting when all was quiet. No 60-Hz power line interference was evident.

Preliminary shot-induced noise tests indicated that ground roll modes of 40 to 57 Hz were generated but could be largely attenuated with the low-cut instrument filters of 90 Hz. At some locations, for example on the west ends of lines 1 and 2, where the marshy surface was extremely undulated, the inboard 8 to 12 traces close to the shot showed marked ground roll effect, but as a general rule ground roll was not a major problem.

The surface shots from the Seisgun produced an airwave at a velocity of about 1,050 ft/s with apparent frequencies of 155 to 160 Hz. Most of the field records show this noise train. There was no practical way to mask the energy in the field, but it was easily muted out in processing.

Source comparison tests were conducted on line 1 and later on line 3. Steeples (7)[1] had conducted high-resolution tests using a small-bore 30.06 rifle adapted to a Seisgun configuration and had recorded frequencies "above 200 Hz with some 300 and 400 Hz signal" on shallow experimental profiles in Kansas. The same source unit was acquired for testing, but in the soft surface clays on both the east and west ends on line 1, the bulk of the impact energy was absorbed and the small-bore unit was useless.

A second comparison was made using 6-in to 3-ft lengths of 200-grain primacord wadded and placed in shallow 4- to 5-ft-deep holes drilled with a portable auger powered by a small two-cycle engine. On line 1 the primacord results were fair to inconclusive compared to results of multiple shots with the 8-gauge Seisgun. It had been anticipated that the small dynamite charges would yield better or at least equivalent energy frequency transmission, but the directed energy of the projectile slugs was comparatively better.

On line 3, the results of several Primacord tests showed slightly better energy penetration at some locations but were not consistently better than the Seisgun results.

Low-velocity weathered-layer data were initially collected on line 1 by recording individual reverse shot

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[1] Underlined numbers in parentheses refer to items in the list of references preceding the appendix.

profiles between each eight station line segments for a total offset of 160 ft. At first, 10-Hz low-frequency geophones were employed with multiple "shots" by simply impacting a metal plate on the ground surface with a 12-lb sledge hammer. The technique works and is traditionally used on many shallow surveys. It was found, however, that equal or better "first arrival" information could be obtained with half the effort and time by using the Seisgun and 40-Hz detectors in a normal production mode of single-end recording. Consequently, the reversed short spread refraction profiles were discontinued.

PRODUCTION RECORDING

A procedure was used in the survey to achieve a 12-fold CDP stack with an 8-channel recording system, wherein detector and shot point stations are equally spaced at 20-ft intervals on the surface, yielding subsurface reflection points at 10-ft intervals. Three primary eight-trace records with different offset distances are recorded from the same shot point location by simply advancing the instrument CDP roll-along switch in eight-trace increments. Later, in processing, the records are sorted by a computer program and placed end to end to form a single 24-trace file pertinent to the specific shotpoint. Subsequent processing is the same as with any 24-trace recording to yield a 12-fold stack.

The rationale for employing an eight-trace recording system for the survey was based primarily on the following considerations: (1) the need for vertical stack (summing) capability for use with a low-energy, high-frequency surface source, (2) the limited availability of instrument systems with the capability both to vertically stack multiple shots *and* to record high sample rates (1/2 to 1/4 ms) to acquire high-frequency data, and (3) an additional advantage provided by use of a limited spread system, wherein total shot energy can be tailored to specific offset distances, i.e., many more shots can be applied to the far traces without "overshooting" the traces near the shot point or increasing the amplitude of coherent noise.

At the outset of recording it was found that, in combination, the large slug and shot blast from the first and second shots of the Seisgun penetrated the surface soil to a depth of about 4 ft and produced a 4- to 5-in-diam hole. Succeeding shots, however, did not deepen the hole, and energy transmission was better. Apparently, the initial shot-slugs flattened and compacted the soil to form a denser medium in the vicinity of the shot. Consequently, as a general procedure, two initial shots were made at each shotpoint without a record to "set up" the hole, after which the succeeding shots were recorded.

The results of the survey show that 12-fold CDP coverage is probably the *minimum* stack that will yield reasonable results in this region.

Field recording showed frequencies up to about 250 Hz. The processed data show probably valid signal of about 300 to 400Hz. Reasonable energy was recorded in the critical coal horizon window between 0.100 and 0.200 s. All shots were recorded to 1.0 s.

DATA PROCESSING

Essentially conventional processing procedures were applied except that (1) certain adaptations to the computer program were necessary to accommodate processing of the broad band width data, (2) additional effort was made in derivations and application of trace static corrections, and (3) final display parameters were increased by a factor of 10 to facilitate data interpretation.

It is fairly certain that significant reflection frequencies above 500 Hz had not been recorded in the field; however, it was decided to process the data at the same 1/4-ms sample rate as recorded to assure retention of the highest frequencies on tape. The effective band widths of the field recording filters were 90 to 500 Hz and 90 to 1,000 Hz.

Few data processing centers have programs in standard use that are written to accept high-resolution 1/2- to 1/4-ms sampling. For this situation, program default values were modified where applicable, but an acceptable procedure of using a parameter multiplier of 4× and processing the 1/4-ms data at a representative 1-ms sample rate was generally adopted.

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